# The Bandit: An Automated Vision-Navigated Inspector Spacecraft

Michael Swartwout[*], Jared Macke[**], Keith Bennett[**] and William Smart[**]

*Department of Mechanical and Aerospace Engineering, Washington University in St. Louis, St. Louis MO 63130
(314) 935-6077, mas@me.wustl.edu

**Department of Computer Science & Engineering, Washington University in St. Louis, St. Louis MO 63130

**Abstract.** Further improvements in the reliability and operational lifetime of space systems require the ability to detect and repair problems on-orbit. The detection task would be aided by detailed, on-demand images of any region of the vehicle's exterior. One proposed method to do this is a deployable, maneuverable, camera-carrying "inspector" spacecraft. Such systems should be small, lightweight and low-cost to minimize changes to the parent vehicle, and, ideally, they should be capable of docking for re-use and safe stowage.

Researchers and students at Washington University propose the Bandit, a prototype inspector spacecraft, as part of the 25-kg Akoya University Nanosatellite Program. A 1-kg inspector releases from its parent vehicle, performs a visual inspection of the exterior, and re-docks. The carbon-fiber shell of the inspector contains an imager, transceiver and cold-gas propulsion system; the Akoya spacecraft holds the docking mechanism, another transceiver and image processing and flight control hardware. The Bandit is automatically controlled by Akoya using video images aided by exterior visual markings; ground controllers provide high-level directions.

This paper outlines the mission profile and major subsystems of the Bandit, with emphasis on flight control, vision and image processing subsystems. Early prototyping and flight-readiness plans are also discussed.

## Introduction

Further improvements in the reliability and operational lifetime of space systems require the abilities to detect and to repair problems on-orbit. The detection task would be greatly aided by detailed, on-demand images of any part of the vehicle's exterior. One proposed solution is to add a maneuverable, deployable, camera-carrying "inspector" spacecraft. Such systems should be small, lightweight and low-cost to minimize the design impact of the parent vehicle. And, ideally, such inspectors should have a docking capability to ensure re-use and eventual safe disposal. Similarly, it is advantageous for the inspector to be autonomously guided, freeing the operators to focus on the mission data rather than flight controls.

There have been several successful demonstrations of inspector spacecraft and related technologies. DARPA is sponsoring Orbital Express, a demonstration of autonomous on-orbit satellite servicing.[1] In 2000, Surrey Satellite Technology's 6.5-kg SNAP-1 deployed from the upper stage of its launch vehicle and returned images.[2,3] In early 2003, the 28-kg Air Force Research Laboratory (AFRL) XSS-10 microsatellite deployed from the last stage of a Delta II rocket and demonstrated line-of-sight guidance within 100 m of its target.[4] Both of these missions made use of imaging systems for operations and navigation, and both vehicles carried their own propulsion systems. However, neither of these missions involved re-docking after deployment, and both missions were controlled by ground operators.

Therefore, researchers and students at Washington University in St. Louis (WU) are designing a prototype inspector spacecraft, dubbed the Bandit; this mission is a flight experiment on Akoya, a student-build spacecraft in development under the Air Force Research Laboratory's University Nanosatellite program.

The Bandit mission is not a full demonstration of an inspector spacecraft; the flight camera cannot provide high-resolution imagery of the spacecraft exterior. Rather, it is a demonstration of key enabling technologies for inspector spacecraft: repeatable docking, close maneuvering near a parent vehicle, and automatic, image-based navigation. These technologies will be tested in phases, with total flight time on the order of hours.

The 1-kg Bandit will release from the 25-kg parent vehicle, perform a visual inspection of the exterior, and re-dock. The Bandit vehicle consists of a carbon-fiber shell containing an imager, transceiver and cold-gas propulsion system; the Akoya spacecraft holds the docking mechanism, another transceiver, and image processing and flight control hardware. The Bandit is steered by software on-board Akoya using video images aided by visual markings on Akoya's exterior. Ground operators will supervise the experiment's progress and provide high-level instructions.

**Project Aria**

Akoya and Bandit are being developed as part of Project Aria, a multidisciplinary educational, research and outreach program of the School of Engineering and Applied Sciences at Washington University.[5] Past Aria programs include passive science experiments on four Shuttle flights (with four more approved), and integration and flight operations of the Sapphire microsatellite. Current programs include a high-altitude balloon testbed, a high-altitude glider return vehicle, and a passive K-12 science payload on an upcoming NASA Antarctic long-duration balloon mission.

Project Aria is chartered to provide hands-on design, test and operations experiences for pre-college, undergraduate and graduate students. Therefore, Aria programs reflect a preference for student-designed, student-built systems. Such design choices often are made despite an increase in risk or a reduction in performance. In all Aria programs, the most important mission products are students.

**The Akoya Nanosat**

The Bandit is a proposed experiment for the Akoya Nanosat, which is part of AFRL's Nanosat-3 design competition. The winning entry among the 13 participants will be provided a flight opportunity in or after the last quarter of 2005.

Akoya is a 25-kg spacecraft in development at WU, based on the Sapphire,[6] Opal[7] and Emerald[8] designs. It is an octagonal cylinder composed of stacked aluminum honeycomb trays with body-mounted side and top solar panels. When in eclipse, the vehicle will draw power from a single NiCd battery pack, providing 15 W total for its regulated 12V and 5V bus lines. The vehicle will be gravity-gradient stabilized, with magnetic torquer coils for damping and some yaw control. The experimental command & data handling system is based on the $I^2C$ and Dallas 1-Wire protocols and is built by Santa Clara University (SCU).[9] Santa Clara is also providing the 9600 baud packet communications subsystem which will operate in the UHF and VHF bands.

Akoya will controlled by ground operators at WU, SCU and partner universities. Other proposed Akoya experiments include a spherical imaging system (OrbitVision), a test boom and control vane for small solar sails, a K-12 science package, and several experiments in autonomous event detection and response.

If both of the OrbitVision and Bandit experiments fly, there will be close coordination between the two; the OrbitVision cameras could be used to observe the Bandit as it maneuvers around Akoya. Similarly, if all goes well, the Bandit inspector could be used to verify the deployment and operation of the solar sail boom.

**Paper Overview**

The remainder of this paper provides a mission outline and system description of the Bandit, emphasizing structural & docking design and image-based navigation. Test plans for the two-dimensional testbed will be described, followed by a discussion of flight risks. The paper will conclude with flight-readiness plans and observations.

## Bandit Mission Overview

The Bandit mission is divided into phases, beginning and ending with the inspector docked to the Akoya parent vehicle. Each phase consists of a set of standard maneuvers; subsequent phases build on previous maneuvers to create new activities. Therefore, each phase is an incremental stage in mission success. The mission phases are outlined in Table 1 and detailed below.

A phase may be repeated several times depending on its outcome. Phase activities may also be re-written based on in-flight behavior of the imaging and propulsion subsystems.

**Phase 0: Docking**

This phase provides the minimum success for the Bandit mission: the inspector is released, backs a few centimeters from the docking ring, and re-docks. Because the Bandit never leaves the cone of the docking structure (see below), neither attitude control nor image-based navigation are needed for Phase 0. A simple forward propulsive thrust will cause the vehicle to dock again.

Phase 0 verifies functionality of the release mechanism, separation sensors and forward thruster. It may be repeated as many times as the operators need to verify that all components are functioning properly. Each Phase 0 test takes 20 seconds and 3 mm/s of velocity impulse.

**Table 1.** Bandit Mission Profile, Phases 0-4.

| Phase | Maneuvers | Duration (sec) | ΔV (mm/s) |
|---|---|---|---|
| 0 | Release | 10 | 1 |
| | Dock | 10 | 2 |
| 1 | Release | 300 | 6 |
| | Park | 300 | 6 |
| | Dock | 300 | 6 |
| 2 | Release | 300 | 6 |
| | Park | 30 | 2 |
| | Inspect | 600 | 52 |
| | Park | 30 | 2 |
| | Dock | 300 | 6 |
| 3 | Release | 300 | 6 |
| | Park | 30 | 2 |
| | Inspect | 150 | 26 |
| | Midcourse Park | 30 | 33 |
| | Inspect | 450 | 40 |
| | Park | 30 | 2 |
| | Dock | 300 | 6 |
| 4 | Release | 300 | 6 |
| | Park | 30 | 2 |
| | "Escape" | 300 | 350 |
| | Acquire | 10 | 5 |
| | Rendezvous | 300 | 350 |
| | Inspect | 150 | 26 |
| | Park | 30 | 2 |
| | Dock | 300 | 6 |

**Phase 1: Parking**

This phase demonstrates image-based stationkeeping and docking. The Bandit is released and backs away one meter from Akoya; it then holds this position for a set time before returning to dock. This "parking" position is such that the Bandit is aligned for docking; it also is the starting position for all subsequent maneuvers. The vehicle navigates by keeping the Akoya spacecraft in a specified position and orientation within the camera's field-of-view. The imaging system will also be used to maneuver the vehicle for docking.

It is anticipated that Phase 1 will be repeated at least twice to demonstrate parking times of 30 seconds and 5 minutes. It may also be repeated to test docking performance under several lighting conditions. Phase 1 demonstrations will take less than 15 minutes and less than 18 mm/s.

**Phase 2: Inspection**

This phase demonstrates image-based navigation under the disturbance effect of relative motion between the vehicles. The Bandit is released to its parking position; from there, it will enter into an "orbit" around Akoya, completing one revolution while keeping the spacecraft within its field of view. At the end of its orbit, it will return to the parking position and orientation, then dock. Phase 2 will be repeated for several "orbit" orientations and durations. Phase 2 demonstrations take about 20 minutes and 71 mm/s.

**Phase 3: Close-Up Inspection**

The third phase is a repeat of Phase 2 with a mid-course parking maneuver. Midway through the inspection orbit, the vehicle will "park" relative to one side of Akoya and move within 1 m. It will hold this orientation for 30 seconds, then resume its inspection orbit, stopping at the original parking position before docking. Phase 3 demonstrations will take about 20 minutes and 115 mm/s.

**Phase 4: Rendezvous (Optional)**

The first three phases serve to characterize the in-flight performance of the imaging and navigation subsystems. If these systems perform as expected, a fourth phase may be attempted. This phase simulates the inspection of a new object or a situation in which the inspector has lost its attitude and position reference, demonstrating re-acquisition of the inspection target and rendezvous.

Phase 4 begins with the basic release to parking. From there, the Bandit will maneuver away from Akoya to a distance of approximately 50 m. At this distance, the vehicle will be a few pixels on the imaging system. The Bandit's navigation algorithm will be re-set such that it no longer "knows" the reference position of the parent vehicle. At this point the Bandit will rotate until it acquires the parent vehicle, then maneuver to bring itself within a few meters. It is likely that an inspection orbit will be needed to return to the parking position and docking. A rendezvous demonstration will take about 25 minutes and 750 mm/s of thrust.

**Extended Missions**

If all phases have been successfully completed and sufficient fuel and power margins exist, several extended missions have been planned. These missions include: new image processing algorithms (such as ignoring the external markings), close-up inspection (10 cm or less) and more challenging rendezvous scenarios (100 m or more initial distance).

## System Description

The Bandit mission is a student-led initiative; thus it relies on nontraditional design and fabrication practices managed by a rigorous systems engineering process. The Akoya nanosatellite mission imposes severe restrictions on mass, size, and downlink bandwidth, as well as an aggressive development schedule, but it provides the possibility of a near-term low-cost flight opportunity. Similarly, the close coordination between the Akoya and Bandit teams enables the Bandit team to use Akoya assets for its mission and to share some risk with the Akoya project.

Therefore, the Bandit team has accepted a high-risk system architecture that offsets mass and cost constraints while maximizing the potential payoff. Because the main goal of the overall Akoya & Bandit programs is to train students in space systems engineering, it is not an exaggeration to say that a well-built, well-tested and fully integrated system would be a success regardless of the on-orbit performance.

The Bandit system has three space elements: the deployable inspector spacecraft, docking mechanism, and flight control electronics. The overall system block diagram is shown in Figure 1. Each of these elements is described below, as well as the ground control.

Several unusual design decisions are worth noting. Because of the extremely small size of the inspector spacecraft and the availability of a capable processor on Akoya, image processing and is performed on the parent vehicle. Similarly, bandwidth constraints force real-time control of the inspector to be shifted from ground operators to the Akoya spacecraft. The Bandit itself receives only simple on/off commands to power the camera or one of the five thrusters, and it broadcasts its camera images whenever the camera is on.

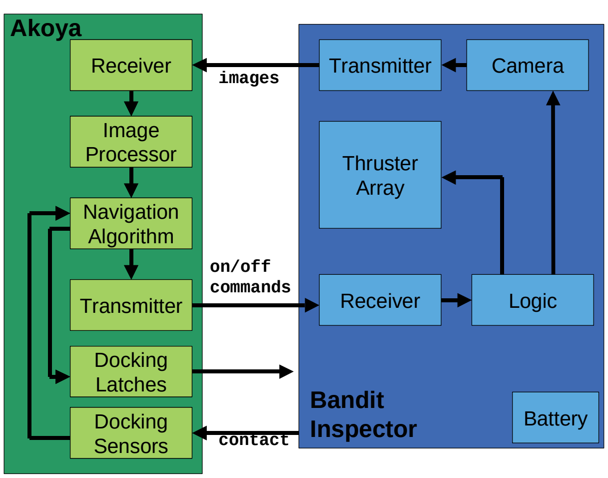


**Figure 1.** Bandit block diagram.

### Inspector Spacecraft

The Bandit is essentially a flying camera, consisting of an imager, battery, transceiver, control electronics and propulsion system contained within a carbon-fiber shell. The mass breakdown for the inspector is shown in Table 2.

**Table 2.** Inspector spacecraft mass budget.

| Component | Mass (grams) |
|---|---|
| Propulsion | 510 |
| Batteries | 100 |
| Shell | 15 |
| Imaging system & transceiver | 125 |
| Internal frame | 100 |
| Control electronics | 50 |
| *Margin* | *100* |
| **Total** | **1000** |

As shown in Figure 2, the conical shell eliminates roll dependencies in docking, and its shape helps minimize the effects of translational and rotational errors during docking. The attachment point for the docking mechanism's latch arms is a lip on the inspector's shell. The lip is near the base because the Bandit's mass center will be near the base, due to the heavy propulsion system. This placement will minimize the effects of launch vibration on the docking mechanism.

The Bandit shell is a two-layer 0/90 prepreg carbon fiber layup made of two pieces and then epoxied together. Carbon fiber was chosen over metals because of the need for a very lightweight shell with complicated geometry. The shell is not load-bearing, however; all internal components will be bolted to an aluminum-frame tower that attaches to the lip. A prototype shell and docking mechanism was completed in December 2002; the revised design is under development.

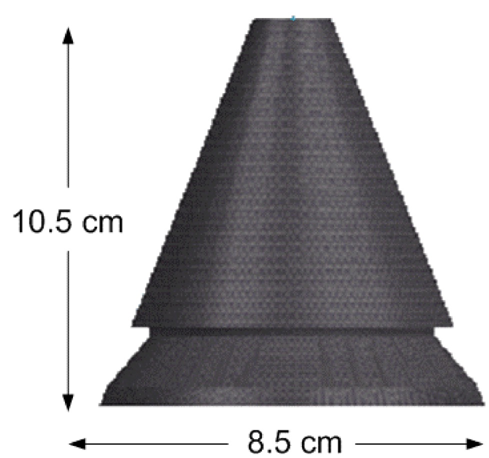


**Figure 2.** Bandit shell.

The camera will be a consumer-grade imaging system similar to the X10 webcam, modified for space flight; this approach was chosen to simplify development and functional integration. The camera will be connected to a dedicated transmitter that will send images back to Akoya. It has not yet been determined whether the broadcast images will be analog or digital; the camera, transmitter and spacecraft-side receiver will be purchased as one system such that the images are available to the image processing system in a standard digital format.

The control electronics are equivalent to the DTMF decoder used in touch-tone phones; the parent spacecraft broadcasts into RF "tones" that the control electronics decode into an on/off signal for the camera and five thrusters. The camera tone will latch the camera on or off until that tone is sent again, whereas the thrusters are activated for only the duration that the tone is sent. Certain tones will activate several thrusters at once in order to enable maneuvers such as turning and reverse. This low-power transmitter will only have a range of a few hundred meters.

The Bandit will be powered by a set of lithium-ion batteries with capacity 450 mA-hr. The driver for battery sizing is the camera and transmitter, which consume about 1 W. Thus, the expected operational lifetime is 5 hours of camera use. No recharge capability exists in the initial Bandit design. Note that the camera can be turned off during the coast phase of many Bandit maneuvers, which will significantly increase the operational lifetime.

The Bandit will be maneuvered by a VACCO ChEMS™ Micro-Propulsion System (MiPS), shown in Figure 3. This fully-integrated cold-gas system uses self-pressurizing butane fuel stored in liquid form. With a maximum fuel capacity of 53 g, it is has a total $\Delta v$ capability of 34 m/s for the 1-kg Bandit. However, the Bandit mission may fly without a full fuel tank in order to minimize flight hazard concerns with the launch vehicle. In any event, the thruster is capable of $\Delta v$ impulses as small as 0.25 mm/s.

**Docking Mechanism**

The docking mechanism, shown in Figure 4, consists of a carbon-fiber shell with three aluminum latch arms driven by a solenoid. The default position of the solenoid and latches is closed; the Bandit cannot be released unless the solenoid is activated and the latches opened. The docking mechanism has been designed such that only one arm is needed to hold the Bandit in place. This mechanism is also used to secure the inspector during launch.

**Figure 3.** VACCO ChEMS™ Micro-Propulsion System. *[Courtesy VACCO.]*

Docking maneuvers are managed by the Akoya flight control, which activate the solenoid as the Bandit approaches. When microswitches indicate that the Bandit is within the docking ring, the solenoid is turned off and the inspector is held in place.

Like the Bandit shell, the docking shell is made from carbon fiber, four layers of 0/90/±45 prepreg. As mentioned above, this material is preferable to metals because of its ease in forming unusual geometries. Note that the docking shell does not carry primary launch loads; the mass of the inspector is carried through the latch arms into the Akoya structure.

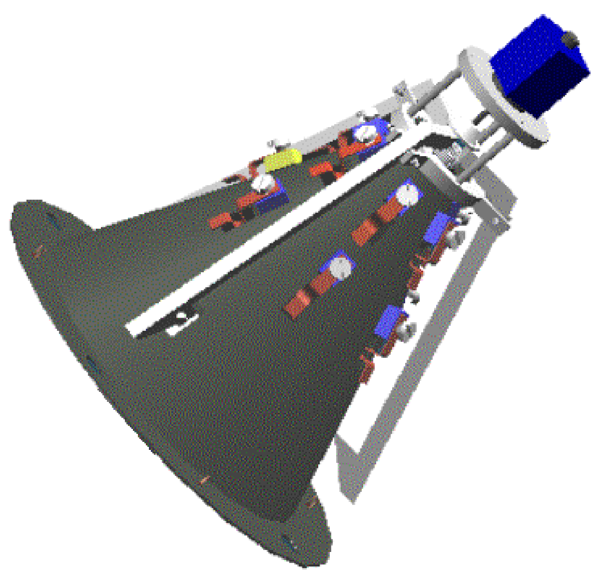

**Figure 4.** Exterior of Bandit docking mechanism with latches in open configuration. This rendering includes optional LEDs to aid in docking navigation.

### Control Electronics and Software

The image processing and flight control functions on board Akoya are handled by an avionics processor shared by several Akoya systems. The processor will be dedicated to Bandit control during all Bandit operations. A dedicated receiver converts transmitted video from the Bandit camera to digital images, which are fed into processor. The processor converts these images into navigation information, which is then converted into navigation commands and relayed to the Bandit. The transmitter is a dedicated, low-power COTS component operating in the VHF band. As discussed above, it broadcasts simple on/off tones used to activate the thrusters and turn the camera on and off.

The flight control software is further discussed in its own section, below.

### Ground Control and Operations

Due to bandwidth limitations, ground operators will not be able to view or control the Bandit in real-time. Operators will initiate experimental phases and receive status updates during the phase. Each phase is set up as a sequence of activities that will be automatically executed, although operators will have the ability to override a sequence, such as forcing a return to docking.

Note that Phase 2 operations and subsequent phases last longer than 15 minutes, which is the expected maximum duration of a pass over the WU ground station. These phases will be handled in two ways. When possible, WU operators will work with partner universities such that the pass is split over multiple ground stations, with each station handing off control authority as Akoya flies over. Secondly, as operators gain confidence with the deployment and parking maneuvers, these maneuvers will be automatically initiated before the vehicle passes into range, and operators will monitor the activity until it ends.

Images from the Bandit camera will be archived on Akoya and available for subsequent downlink. The functional simplicity of the inspector prevents the inclusion of on-board sensors, and thus behavior of the Bandit electronics must be estimated from observations by Akoya and on-board imaging. As discussed above, such an operationally-risky approach was required given the design constraints. These risks are one reason why the Bandit mission consists of many incremental phases.

### Enhancements

If cost and schedule allow, the Bandit experiment will be enhanced with a recharge capability; charging electrodes will be placed on the surfaces of the Bandit and the docking structure such that the Akoya power subsystem can re-charge the inspector's batteries during docking. The original docking design and subsequent prototypes included this capability and no mechanical changes to the docking system are necessary. This change will significant extend the operational lifetime of the Bandit as well as demonstrate an important on-orbit servicing capability.

## Automated Image-Based Navigation

Unlike other inspector spacecraft, the Bandit autonomously navigates using images from its own camera. This is accomplished by determining its position and orientation relative to the parent vehicle, then computing a navigation solution using a linearized gravity model.

### Image Processing

Images generated by the inspector camera can be mined for attitude and position information relative to the parent vehicle. Akoya is a regular octagonal cylinder; the edges and vertices will be marked with LEDs to assist in the identification of each face. Using existing image processing software libraries, an image of Akoya can be converted into a wireframe representation, and that representation can be used to generate relative position and attitude vectors.

The image-processing approach is similar to that used by the autonomous Lewis "wedding photographer" robot developed and demonstrated by one of the authors.[10,11] The Bandit image processing approach will use new algorithms in development to support Lewis.

### Navigation and Maneuvers

Some care needs to be taken regarding maneuvers using the MiPS. As shown in Figure 5 and Table 3, the MiPS is only capable of yaw and roll maneuvers; in order to execute a pitch maneuver, it must first roll 90° such that the yaw thrusters are aligned for pitching. Note also that the system is capable of forward thrust and marginal reverse thrust only. Therefore, to maximize operational performance, all maneuvers are designed to be planar (i.e., yaw corrections only).

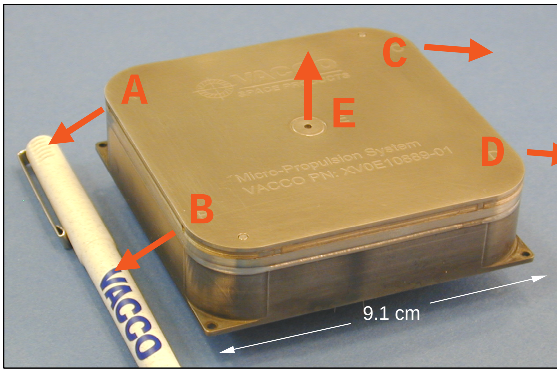


**Figure 5.** MiPS with thrusters labeled. [Courtesy VACCO.]

The orbital equations of motion can be linearized about the nominal orbit of the parent spacecraft; this approach is additionally helpful since the spacecraft is the reference for image processing. Using the conventional Clohessy-Wiltshire (CW) formulation for linearized orbits, a simple Matlab simulation was created to simulate maneuvers. Minimum-fuel maneuvers are developed using this simulation and an algorithm that extends the fuel-optimal multi-impulse time-fixed rendezvous method developed by Chen and Ni.[12]

In the CW frame, the in-plane (xy) motion is decoupled from the out-of-plane (z) motion. The out-of-plane motion is marginally stable; an out-of-plane offset results in a sinusoidal response. However, the in-plane motion is unstable; a vehicle with nonzero in-plane offset will drift away. The dynamics of these behaviors are on the order of the orbit period, which is 93 minutes for the baseline 400 km circular orbit. Maneuvers which last significantly less than an orbit period can effectively ignore the unstable dynamics.

The design of four maneuvers will be outlined: release to parking, parking, inspection and escape. These preliminary maneuvers are designed assuming that the parent vehicle is located at the origin; this approach does not yet consider issues of collision or obstruction.

**Table 3.** Maneuver methodology. [Courtesy VACCO.]

| Maneuver | Thruster(s) |
|---|---|
| + Yaw | AB |
| - Yaw | CD |
| + Roll | AD |
| - Roll | CB |
| + Pitch | +90° Roll Then CD |
| - Pitch | +90° Roll Then AB |
| Reverse ΔV | ABCD |
| Forward ΔV | E |

***Release to Parking Orbit***

The Bandit will be released from Akoya in the –X direction (Earth-facing) and deploy to its parking position at x = -1.0 m. Because the desired transit time is on the order of seconds, the Δv required to reach the parking position can be estimated as (1 / travel time) in m/s; for example a 10-second transit time requires a Δv of 100 cm/s. Increasing travel times greatly reduces the thrust requirements, but the linearized gravity field must be considered. For example, a transit time of 490 seconds requires a Δv of only 1.8 mm/s, but the path is no longer straight, as shown in Figure 6.

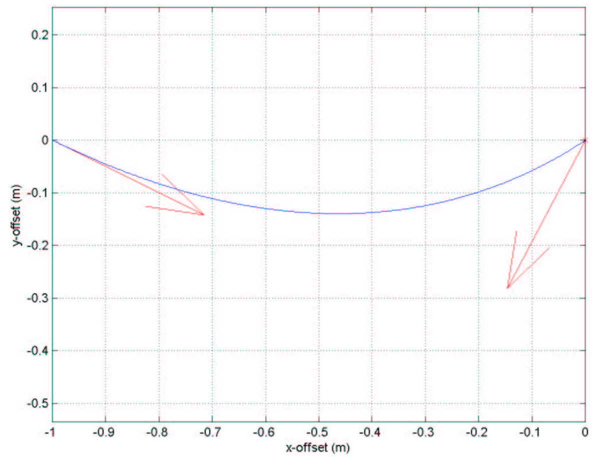


**Figure 6.** Transition from release to the -1 meter parking position in 490 seconds. Arrows indicate thrust directions.

Therefore, a nominal transition time of 300 seconds has been selected, which requires a Δv of 6 mm/s. Note that this impulse value also includes stopping at x = -1 meter. Obviously, this maneuver can be performed in reverse for docking.

***Parking Orbit***

As explained above, the x = -1 meter parking position is not stable; without orbit corrections, the vehicle will drift far from that position in a matter of minutes. A simple solution is to define the parking orbit as a maneuver whose beginning and end points are at the parking position. A family of such maneuvers can be identified and the best one selected depending on the parking time.

A typical parking orbit is shown in Figure 7. For this 1400 second duration (1/4 of an orbit) maneuver, the total thrust required is 3.7 mm/s. If the parking position requires a tighter envelope, then the thrust requirements will change, but not as significantly as the transition to parking. For example, an orbit correction of 0.4 mm/s every 100 seconds will keep the spacecraft within centimeters of the preferred position; in fact, 0.4 mm/s is on the order of the smallest impulse possible. And, over 1400 seconds, this small mid-course corrections only total to 5.6 mm/s, a 1.9 mm/s increase over the orbit of Figure 7.

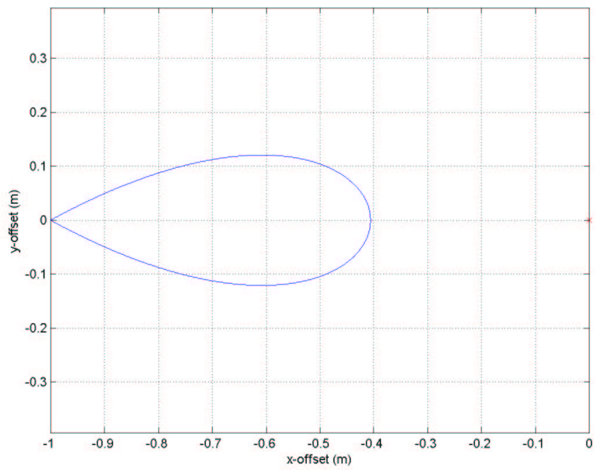


**Figure 7.** Parking maneuver, 1400 second duration.

Therefore, since the parking maneuver is defined as a short duration (5 minutes or less) activity, it is appropriate to correct the drifts on the order of once per minute. A five-minute parking maneuver would require approximately 6 mm/s of thrusting.

### *Inspection Orbit (In-Plane)*

The parking maneuvers discussed above naturally lend themselves to in-plane inspection orbits. As shown in Figure 7, the 1400-second maneuver brings the inspector within 40 cm of the origin. Simply increasing the allowed transit time reveals that the minimum-fuel inspection orbit has a $\Delta v$ of 4.5 mm/s and a duration of 93 minutes. As shown in Figure 8, this inspection orbit is a stable nearby orbit; if the inspector executes the 2.3 mm/s maneuver to get "on" this trajectory, it will indefinitely orbit the parent vehicle. Therefore, this maneuver is the optimal parking orbit for long duration (greater than one orbit period) maneuvers. The inspector is never further than 2 meters from the target.

Much shorter-duration inspections are possible; these are essentially straight-line transfers from point to point. For example, a 10-minute tour of [-1 0], [0 1], [1 0], [0 -1], [-1 0] involves one propulsive maneuver at each vertex, the total $\Delta v$ is 52 mm/s.

### *Escape*

For escape, the inspector is transitioned to a stable nearby orbit 50 meters from the target. Because of power limitations, this transition should take less than 5 minutes, in which case the transition is nearly a straight line. The thrust required is 350 mm/s, significantly more than the other maneuvers. This is one reason why the escape test is in the latter mission phases.

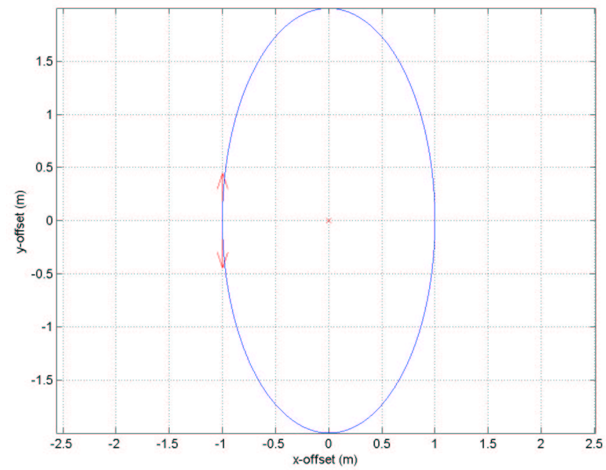


**Figure 8.** Inspection orbit, duration 93 minutes (1 period).

Assuming sufficient power margins (for example, turning the camera off during the coast phase), the optimal thrust drops dramatically to only 49 mm/s for a 64-minute coast. However, as shown in Figure 9, this transition involves a significant drift away from the parent spacecraft and a thrust maneuver when the inspector is pointed away from Akoya (its navigation reference). For all these reasons, the minimum-fuel orbit will not be attempted before the operators have significant confidence in the Bandit's on-orbit behavior.

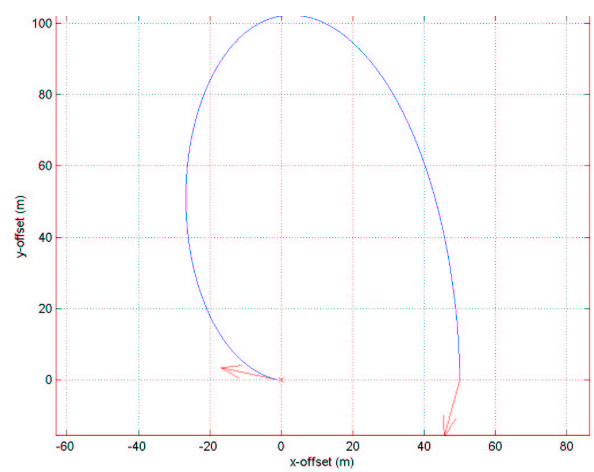


**Figure 9.** Transition to "escape", 64-minute duration.

### *Thrust Budgeting*

All of these thrust calculations assume perfect thrusting and no thrusting required for slewing the spacecraft. Obviously, margin needs to be built into the thrust estimates to account for non-optimal performance and slewing. The design of the Bandit and these maneuvering systems is very conservative and allows for ample margins.

First of all, the Bandit has a moment of inertia of approximately 30 g-cm$^2$; it will take less than 1 mm/s of thrust for any significant slewing. It may be necessary to reduce the pulse size to create reasonable slew rates!

Secondly, each maneuver has been optimized with respect to time and fuel constraints; however, they have not been optimized with respect to linked maneuvers. For example, the 6 mm/s $\Delta v$ requirement for parking assumes that the Bandit is stationary before and after the maneuver; there could be significant savings as the vehicle is transitioned from one maneuver to another.

Most importantly, the MiPS thruster can hold an order of magnitude more fuel than is needed for an extremely ambitious flight plan. A mission that consisted of 10 Phase 0 demonstrations, 5 Phase 1, 5 Phase 2, 2 Phase 3 and 1 Phase 4 demonstration would require less than 1.5 m/s total $\Delta v$; for a vehicle of this mass, the MiPS can hold enough fuel for more than 34 m/s of thrusting. The thrust requirements for these maneuvers are summarized in the Mission Overview section (Table 1).

On a separate note, the CW equations are linear, and thus these results can be easily scaled. For example, if the parking position is selected to be at x = -2 meters, then all thrust values are doubled.

## Ground Testing

In order to validate control algorithms and system performance, several Earth-based testing platforms are being developed. Each test builds upon the previous one, adding flight-equivalent components and creating a more rigorous simulation of the space environment. Once these tests are completed, the Bandit mission will be ready for a flight demonstration.

### 2-D Testbed (Hovercraft)

Bandit subsystems are being demonstrated in Summer 2003 using a two-dimensional testbed. All subsystems except propulsion are included, although not in flight configuration. The 2-D testbed uses a hovercraft platform to demonstrate the functionality of all other subsystems without a specialized testing environment.

The hovercraft concept is shown in Figure 10 and Figure 11. One main fan is used to provide lift with four fans providing yaw and forward/reverse thrusts analogous to the flight propulsions system. The hovercraft operates within the 300 square foot "arena" shown in Figure 12. This matte black arena forms a neutral background that will help initial calibration and subsequent development of the image processing subsystem. This platform will help determine the optimal LED and colored marking arrangements for best image detection.

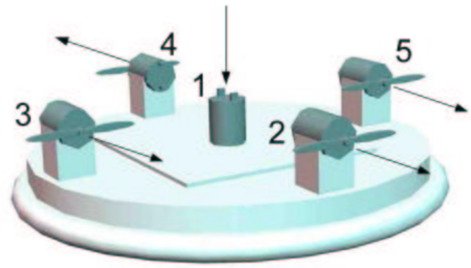


**Figure 10.** Hovercraft platform schematic, with control fans and thrust directions shown.

Initial tests demonstrate both operator-guided and autonomous navigation to set points within the arena and also "cold start" acquisition and rendezvous. By mid-summer the testbed will include docking; the docking cone will be added to the hovercraft and the docking receptacle placed within the arena.

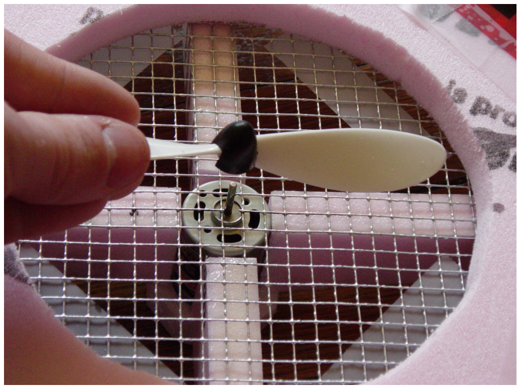

**Figure 11.** Close-up of hovercraft lift fan.

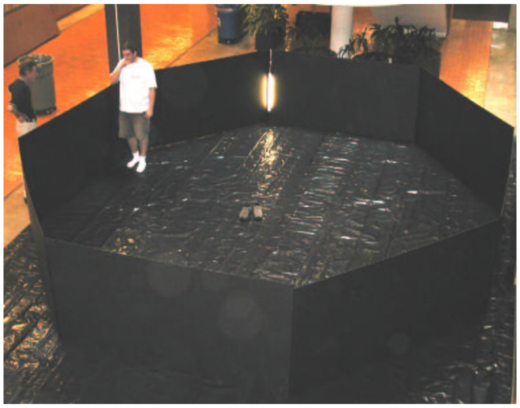

**Figure 12.** Two-dimensional test arena.

**3-D Testbed (Blimp)**

The natural follow-on to the two-dimensional testbed is to repeat the same experiments in three dimensions. This will be accomplished by suspending a prototype inspector spacecraft from a small helium balloon; the vehicle will be made neutrally buoyant in air and capable of roll, pitch and yaw maneuvers. The two-dimensional test arena can be used for these three-dimensional tests.

The first version of the 3-D testbed will use propellers for propulsion and will perform various navigation and docking experiments. The second iteration will involve replacing the propellers with the cold-gas propulsion system. In addition, researchers will experiment with different lighting conditions to verify the robustness of the image processing system.

The 3-D testbed will not be a true six degree-of-freedom demonstration due to the dynamics of the helium balloon and the inability to perform true roll and pitch maneuvers while attached to it. In addition, ambient air will act as a disturbance and excessively damp attitude rates. However, these experiments provide a natural stepping stone between the 2-D testbed and a full microgravity testbed; results from the 3-D testbed will help define the testing plan for the next set of experiments.

**Reduced-Gravity Testbed**

The students developing the Bandit mission will submit a proposal to next year's NASA Reduced Gravity Student Flight Opportunities Program. Selected experiments fly aboard NASA's KC-135A Reduced Gravity Aircraft.

The proposed experiment includes the inspector, docking mechanism and flight control electronics in flight configuration. (Depending on flight safety regulations, a propellant other than butane may be substituted.) The experiment will consist of demonstrating autonomous operation of the building-block maneuvers that make up Phases 0-3, described above. Each reduced-gravity episode lasts about 20 seconds, so the $\Delta v$ requirements of each maneuver will be increased to meet this time frame..

## Risk Management

The Bandit team has identified several areas of mission risk; these issues are described and the mitigation plans are provided.

**Robustness of the Image Processing**

Since Bandit navigation depends on image processing, there is a concern that the high brightness/high contrast visual environment of near-Earth orbit will render this commercial camera ineffective. A rigorous set of ground tests in many lighting conditions are planned to allay these fears. In addition, most phases are short enough that they could be conducted during the eclipse portion of the orbit, where the LEDs of the spacecraft would be the brightest points in the image.

**Calibration**

Proper navigation of the Bandit depends on proper identification of the vehicle markings and proper thruster firings. The imaging system will be calibrated by default; algorithms are being developed to identify specific colors indepedent of intensity. As for thrusters, extensive ground testing will be performed to calibrate their behavior as a function of temperature. If necessary, a thermostat circuit will be added to the inspector to maintain the thruster unit at a more even temperature.

**Disturbances and Thrust Imbalances**

The Bandit must have Akoya within its field-of-view in order to produce a navigation solution. Therefore, any disturbances (such as tipoff rotation during deployment) or thrust imbalances could cause Akoya to leave the field-of-view and/or cause the blurred images. In fact, addressing this concern is one of the primary objectives of Phase 4, in which the Bandit must re-acquire a navigation solution.

Therefore, starting with Phase 0, the Bandit flight control system will have a built-in procedure to account for loss-of-target: the vehicle will first null its rotation (by identifying the axis of rotation of the blurred image), then initial a slow yaw rotation until the target is spotted. (This may require a plane change and second yaw rotation.)

**Anomaly Management**

The Bandit inspector carries no sensors other than its imager. Therefore, operators will have no observability into such basic issues as resource consumption (battery power, remaining fuel) nor diagnostic information such as component temperature. And thus operators will have no effective means to detect, monitor or correct any problems that may occur.

This risk is being managed in four ways: first, the mission profile is defined to provide incremental performance verification; each phase tests additional elements of the vehicle. The experiment is also designed so that the most important tests take place early in the mission, when the fuel and power margins will be high. Third, extensive ground testing of the flight vehicle will provide "open loop" estimation of the fuel and power consumption of various maneuvers. Finally, the Bandit team accepts that this is a high-risk experiment.

As has been noted, the camera and transmitter consume by far the most power; due to the slow nature of the system dynamics, it may be possible to turn off the camera for several seconds or even minutes at a time. This would significantly increase mission lifetime.

## Future Activities

As discussed above, the Bandit team is in the process of developing and testing the 2-D and 3-D testbeds. Those activities will be completed in mid-Fall 2003. If the Bandit proposal is selected, the reduced-gravity tests will take place in early 2004. In either case, final design and fabrication of the Bandit system will commence in spring 2004 and be completed by late summer; all Bandit components are either simple, student-built or COTS hardware. The sole exception is the flight avionics processor on Akoya; that device may not be ready until late 2004.

Several flight spares of the inspector spacecraft and docking structure will be built; during 2004 these devices will be used to further test and refine the image processing and flight control algorithms. More detailed optimization algorithms will be developed to search for more fuel-efficient methods for parking and inspection.

The first Bandit flight opportunity will be in late 2005 if Akoya wins the Nanosat-3 competition. However, the Bandit team will seek out additional flight opportunities regardless of the results of the Nanosat-3 selection.

## Conclusions

The Bandit mission is an ambitious experiment in autonomous docking and image-based navigation near a parent spacecraft. Driven by programmatic and operational constraints, this mission is a high-risk but high-payoff attempt to demonstrate enabling technologies for very small, autonomous inspector spacecraft. The pre-defined maneuvers outlined in this paper provide significant margin over the 34 m/s total $\Delta v$ available to the MiPS propulsion system.

Several of the authors are veterans of both very large and very small space programs, as well as very large and very small educational programs. From that perspective, a significant advantage of the combined Bandit/Akoya Nanosat-3 program is that students are encouraged (forced, actually) to be very innovative in their design approaches in order to overcome very real cost, schedule and functional constraints. At the same time, they interact with industry mentors, reviewers, and safety engineers who encourage (again, force) them to develop sound, rational defenses of their innovative design methods. We feel that this is a wonderful tension in which to place untested engineering students.

One tremendous advantage that university spacecraft have over their professional counterparts is the freedom to fail; we can take risks with a student inspector spacecraft and parent vehicle that cannot (and should not) be taken with a private or government one. We encourage projects at other schools to seek out these high-risk activities for their own missions.

Similarly, it is hoped that the eventual Bandit flight experience will serve as a template (or warning) for other schools in how to structure and manage a university program. The authors have learned a great deal from the earlier waves of student spacecraft and hope that future waves can benefit from our work.

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